Ship Stability & Safety in Intact Condition through Operational Measures

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ABSTRACT

Guaranteeing a sufficient level of safety from the point of view of stability is typically considered to be a matter of design. However, it is impossible to ensure safety only by design measures, and operational measures can then represent a complementary tool for efficiently and cost-effectively increasing the overall safety of the vessel. Time could therefore be coming for systematically considering operational measures as a recognised and normed integral part of a holistic approach to ship safety from the point of view of stability. In this respect, the scope of this paper is to identify open challenges and to provide, in general, food for thoughts for stimulating a discussion on the topic of operational measures, with specific attention to the intact ship condition. The aim of the discussion should be to provide ground for further proceeding towards the goal of implementing a virtuous integrated approach to ship stability safety which gives due credit to effective and robust operational risk control options.

Keywords: *ship stability; ship dynamics; ship safety; operational measures; intact condition*

1. INTRODUCTION

Guaranteeing a sufficient level of safety from the point of view of stability is typically considered to be a matter of design. It is indeed often assumed that the required level of safety is to be guaranteed by implementing proper passive measures at the design stage, in the form of design characteristics (hull shape, subdivision, systems redundancy, etc.) and in the form of limitations on the acceptable loading conditions.

The matter of safety-by-design, both in intact and damaged condition, has been, and of course still is on top of the agenda, especially regarding the rule-making process. However, it is impossible to ensure safety only by design measures, and design rules implicitly assume a certain level of knowledge, skills, experience and prudence of ship masters and crew. These human factors, which are commonly referred to as "good/prudent seamanship", represent, therefore, a crucial aspect in determining the ship level of safety. The skills of existing officers are however challenged by rapid development of unconventional ship types and shipping solutions. In some dangerous, or potentially dangerous, operational situations, it can therefore be a great challenge for the ship officers to take the most appropriate decisions for reducing the risk level. Such situations can be effectively addressed by operational measures aimed at providing a decision support for the crew. The implementation of operational risk control options can represent a valid tool for efficiently and cost-effectively increasing the overall level of safety of the vessel, both in intact and in damaged condition, also in those cases for which design variations would not be cost-effective. This is typically the case with issues associated with dangerous dynamic stability phenomena in intact condition.

In fact, looking at numerous accidents reports it can be easily understood that several accidents could have been avoided, or at least mitigated, by implementing appropriate operational countermeasures. Depending on the case, such operational risk control options could be aimed at the prevention of the occurrence of the accident (measures aimed at the reduction of accident frequency/likelihood) or at the mitigation of its consequences.

Although operational measures become effective during the actual life at sea of the vessel, the combination of planning and implementation of such measures involves both the design and the operation phases of the vessel. It is therefore needed to properly "design operational safety measures", both for intact and for damaged condition. Indeed, operational measures are expected to be of different nature and to follow different approaches when considering an intact condition (a "normal state" of the vessel) and a damaged condition (an "abnormal state" of the vessel).

As a result, guaranteeing safety through operational measures is linked with various aspects of the vessel (hull shape, ship handling, subdivision, cargo handling, systems design, etc. etc.), with different phases of the vessel's life (from concept design to actual operation at sea), and with different stakeholders (ship officers, ship owner, cargo owner, shipyards & designers, class, administration).

It can therefore be understood that the concept of "ship stability & safety through operational measures" embraces a variety of conceptual, theoretical, technical, regulatory and educational challenges, with consequent opportunities for research and development. The combination of passive design measures, with active operational measures, can therefore represent a virtuous holistic approach for increasing, in a cost-effective way, the overall level of safety of the vessel, and this concept is further elaborated in this paper with specific attention to the intact condition.

Present intact stability IMO/SOLAS regulations and class rules are mostly "design oriented" and based on an implicit "passive safety" concept. In this context, operational aspects are given a limited attention, often in the form of qualitative, more than quantitative, indications. As a result, operational measures aimed at increasing the overall safety level of the vessel are put in place by ship owners and operators on the basis of a mostly voluntary, and not harmonised, approach.

This situation, where operational safety measures are neither facilitated nor sufficiently normed by the regulators, does not promote the implementation of approaches aimed at increasing safety through proper and cost-effective operational measures. The eventual result is a lack of promotion of holistic approaches to safety, with consequent missing of opportunities for a potential increase of the fleet safety level.

An example of what the shipping system is possibly missing in terms of potential increase of safety can be found by looking at the experience from a European PCTC operator. In such case, the occurrence of large amplitude motions, associated with phenomena driven by variations of restoring in waves, have been significantly decreased by implementing a holistic pro-active framework including a chain of activities: design optimization to ascertain ships' hull forms which are sufficiently robust for their intended service (using extensive numerical simulations and model experiments); continuous recording of ship motions and wave measurements with associated analysis and follow up (particularly in case of occurrence of dangerous events); education of all officers (with particular reference to the dangerous phenomena the vessel can be prone to); and onboard installation of operational guidance systems. As can be noticed, such activities embrace all the phases of the life of the vessel, and are targeting the vessel design, the vessel operation, and the education of the crew. The implementation of such a risk management framework was eventually successful, leading to a reduction of parametric rolling events to a very low rate (of the order of about one per five ship-years for the latest generation of vessels).

There are therefore many opportunities for research and development associated with the idea of giving a more systematic and quantifiable importance to operational measures. At the same time, however, there are also numerous challenges. Some ideas regarding opportunities and challenges have been collected in the following, where the discussion is split in three sections, namely: design, regulatory and classification aspects; tools and methodologies; implementation in operation. However, a sharp separation proved to be very difficult since several of the given considerations are actually conceptually spanning more than one, and in some cases, all the three sections. As a result, some topics appear in more than one section taking, however, a different flavour depending on the perspective they are looked from.

2. DESIGN, REGULATORY AND CLASSIFICATION ASPECTS

Presently, ship stability safety in intact condition is normed by “design oriented” IMO/SOLAS regulations or class rules. The design approach is typically aimed at verifying specific loading conditions and at determining limitations in terms of acceptable KG values, to guarantee a “sufficient static roll restoring” according to specific requirements. Fulfilment of such requirements is implicitly assumed to guarantee a “sufficient level of safety”.

Some general indications are given by regulations regarding the risk involved in having too large static restoring, since this can lead to excessive accelerations. However, such indications do not typically translate into quantitative limitations on GM. Some quantitative indications regarding too large metacentric heights can be applied in the preparation of the cargo securing manual, for those vessels for which this relevant.

The main weakness of such approach is that the criteria used for the determination of acceptable/unacceptable loading conditions are mostly semi-empirical in nature, and do not provide explicit information regarding the possibly dangerous phenomena a vessel could be prone to in a specific loading condition. Furthermore, in some cases, existing regulations do not sufficiently or properly cover certain dangerous phenomena, which are typically associated with large amplitude ship motions under the action of wind and waves.

As a result of this situation, it might happen that a vessel may undergo crew injuries or cargo loss or damage in heavy sea despite fulfilling existing regulations. Conversely, it might happen that a vessel, marginally complying with existing regulations, still has a sufficient level of safety potentially allowing for a further increase of payload and, thus, profitability. In addition to this, the strongly semi-empirical and statistical nature of present regulations does not provide the master with any information regarding the expected behaviour of the vessel at sea. The lack of information, in turn, can lead the master to take wrong decisions in case of a dangerous situation (e.g. selecting speed and/or heading in facing harsh environmental conditions). Also, the present regulatory framework is not designed for incorporating active operational measures as a means for guaranteeing the required level of safety in certain specific, potentially dangerous, conditions.

The mentioned limitations in the prevailing regulatory framework have recently been tackled, conceptually, in the development of the IMO Second Generation Intact Stability

Criteria (SGISC). Indeed, in the framework of SGISC, specific criteria are developed for specific dangerous stability phenomena in waves. This allows identifying, at the design stage, the type of phenomena the particular vessel is prone to. The identification of such phenomena becomes clear with the determination of the governing criteria, and associated failure mode, in the definition of acceptable/unacceptable loading conditions. It is worth noting that, because these criteria are based on a dynamic approach, the usual concept of "limiting GM" is, in principle, abandoned, and this can potentially lead to problems on how to treat this situation from an approval (Administration, or Class on behalf of the Administration) perspective.

In addition, the framework of SGISC allows guaranteeing, in principle, a sufficient level of safety by means of a combination of design requirements and of properly developed ship-specific operational guidance. Alternatively, it is also possible, in principle, to approve the vessel, in the specific loading condition, subject to the fulfilment of some specific operational limitations. "Operational limitations" are herein intended as limitations on the overall operability of the vessel in specific loading conditions (e.g. operations allowed only in certain geographical areas/sheltered waters, or up to a certain significant wave height). On the other hand, ship-specific "operational guidance" is intended as a detailed recommendation to the master on how to handle the vessel, in a specific environmental condition, to reduce the likelihood of inception of "stability failures" to an acceptable level.

It can therefore be seen that the envisioned framework of SGISC gives significant importance to ship-specific operational measures (operational guidance, or operational limitations). Actually, the framework of the SGISC can be seen as shift of paradigm, going from the current situation where ships are regarded as safe when designed and loaded in accordance with the current stability criteria assuming they are just operated on the basis of generic good seamanship, to a situation where ships would be designed considering the possibility of also developing ship-specific operational guidance contributing at keeping the likelihood of stability failures below an acceptable limit. The present target date for addressing "guidelines for direct stability assessment" and "requirements for development of ship specific operational guidance" within SGISC has been set to 2017. The SGISC framework is then supposed to be initially implemented as non-mandatory regulations through the 2008 IS Code, and a possible mandatory application is therefore likely far away in time. Under such a situation, a series of questions arise. To what extent will these new voluntary criteria actually be used if they are not forced by a mandatory framework? How many shipping companies/shipowners will dedicate resources to fulfill these criteria if they are non-mandatory? Will the owners/designers be interested in a pro-active verification of non-mandatory criteria, in view of a possible future mandatory application, or in view of having a better understanding of the dynamic characteristics of the vessel? Will this lead to a wider, more informed, introduction of operational-oriented measures? And how could operational measures be used to increase the safety of some of existing ships that obviously would benefit from stability and safety improvements, but which will not be affected by the new criteria?

However, irrespective of the specific regulatory framework, it is clear that efforts should be spent, in general, to introduce operational measures in the design process, as viable and accepted risk control options. Indeed, implementing operational measures can represent a cost-effective way for increasing safety and, also, competitiveness. An example in this respect can be found in case of inland navigation, where suspension of navigation is sometime introduced in case of too harsh weather conditions (typically wind). In some cases, navigational limitations based on weather conditions are also introduced, on a local basis, for sea-going vessels (to avoid, e.g., port entrance problems). However, a vessel able to operate safely in such harsh conditions could become more competitive, if the cost-effectiveness analysis indicates so. Similar considerations could also apply to vessels operating in sheltered waters, on specific routes, etc.

Implementing such an approach is not free from technical and regulatory challenges, which, at this moment, have not really been sufficiently addressed. As a result, several questions are open and more are likely to come.

Operational limitations could be introduced by changing the reference environmental conditions for the evaluation of intact stability criteria, when this is feasible according to the structure and background of the criterion (this is doable, for instance, at Level 2 vulnerability assessment in the framework of SGISC). The vessel should then be approved with such limitations noted. Operational aspects are presently under responsibility of the Administrations. In presence of operational limitation, it could be necessary for the master to demonstrate the compliance of the planned travel (loading condition, route and associated weather forecasts) before leaving the port, and such plan should be approved by the Administration. It is worth noting at this stage that operational limitations are well-known in rules for classification of vessels for combined river-sea or sea-river navigation, and therefore some experience could be gathered from that context. In the same context, approaches have also been developed in order to allow the operation of inland vessels (with few modifications) in the coastal maritime stretches up to a certain, pre-computed, significant wave height. It is however evident that having this procedure in place for a large number of sea-going vessels would require significant procedural efforts.

In case of development of ship-specific operational guidance, three main possible means can be envisaged for providing such guidance to the master: pre-computation at the design stage, real-time computations on board during operation, real-time computations onshore during operation. In addition, a combination of these three approaches could also be considered as an option. Each of these approaches presents pros and cons from the technical and the regulatory perspective, which so far have not yet been deeply investigated.

From a regulatory perspective, one fundamental issue is the definition of the type software, and associated underlying mathematical model, which can be accepted for preparing ship-specific operational guidance. This aspect has to do with the verification, validation and accreditation process, which should be expected to eventually end up in an approval. At this moment, different options are on the table regarding possibly applicable mathematical models, ranging from simplified 1-DOF models intended for being used for single specific failure modes, up to 6-DOF hybrid tools simulating a vessel free running in wind and waves. Of course this wide spectrum of possibilities needs to be standardised to obtain a uniform application of the regulations.

Regarding how to prepare ship-specific operational guidance, on the one hand, one could be tempted to think that a large number of pre-computations should be carried at the design phase. Results of such computations should then be processed in order to give information to the master on how to safely handle the vessel in dangerous environmental conditions. Such information could then be provided in terms of, e.g. polar diagrams (or any other type of relevant representation) reporting some measure of stability failure. On one side, an advantage of such pre-computed operational guidance is that they could be approved, likely by the Class on behalf of the Administration, already in the design stage. On the other side, however, this could be a difficult approach, for a series of reasons. The first problem is the large number of computations to be carried out, because the set of scenarios to be checked could become huge: different loading conditions, different wave conditions (separating at least swell and wind waves, considering different significant wave heights and characteristics spectral periods), different wind conditions (in terms of mean wind, gustiness spectrum, relative direction with respect to waves), different wave headings, different ship speeds, etc. All these combinations would eventually lead to a very large matrix of simulation scenarios. Another issue to be taken into account when considering the preparation of pre-computed ship-specific operational guidance has to do with the modelling of the environment. Indeed, although typical spectral models can be introduced in the pre-computation phase for both wind and waves, it is also known that the actual environmental conditions can differ significantly from the idealised models. As a result, wind and wave spectra encountered at sea will not correspond, in general, to the ones assumed in the pre-computations. How to use, then, data obtained from pre-computations in such cases? And how to "approve" an instrument, with associated methodology, intended for carrying out this inference? Connected to this, there is also another open question: what level of approximation can be accepted in the representation of the actual environment through simplified idealised parameterised models (with a reduced number of parameters), while still keeping the ability of reasonably identifying the possibility of occurrence of dangerous situations? In short, how much can the description of the environment be simplified, while still keeping a sufficiently accurate prediction of ship motions for identifying dangerous scenarios?

If, alternatively, ship-specific operational guidance would be designed to be potentially based on real-time calculations using the environmental conditions locally encountered by the vessel, this approach could ideally solve some of the issues associated with pre-computations at the design stage. At the same time, the real-time approach would lead to several challenges from the point of view of the approval process, depending on how the computations are carried out. Indeed, real-time computations could be carried out, in general, onboard or onshore. These two alternatives are associated with different levels of available computational resources and information. As a result, a real-time system based onboard (characterised by limited computational resources and limited data access due to satellite bandwidth limitations) would likely be significantly different from a real-time system based onshore (where computational resources and data access are no longer an issue). Such difference in the system would reflect, on one side, on the type of tools and methodologies which can be applicable. On the other side, such difference in the computational system and associated approaches would also reflect in differences in the approval process.

Another issue to be addressed is the definition of "stability failure" for a proper integration within a regulatory framework. When speaking about operation, there could be different types of "failures" with escalating levels of severity, ranging from passengers' severe discomfort, to cargo shifting/loss/collapsing, up to ship capsize. Such types of failures are typically defined by appropriate limits of angles (usually roll, but also pitch) and/or accelerations. In addition, it could be necessary to provide specific "failure conditions" for different types of vessels and/or different types of cargo onboard. For instance, in case of cargo vessels, "failure conditions" need to be defined to avoid the occurrence of cargo shift, cargo loss, or possible cargo collapsing, taking into account the specific vessel, transported cargo and associated lashing arrangement. Then, the most critical mode of cargo failure will depend on the specific case. For instance, in case of inland navigation, the sliding, with possible loss, of non-secured containers can become the governing cargo-related failure condition, while this is typically not the case for sea-going vessels which transport secured containers.

A further challenge for a proper application of ship-specific operational guidance is associated with a sufficiently accurate determination of the parameters of the actual ship loading conditions, which are relevant for dynamic stability computations. From the perspective of "classical" intact stability criteria, a check of the compliance of the loading condition can be carried out by knowing the position of the (solid) centre of gravity and free surface effects (e.g. by tanks' sounding). Accurate knowledge of these parameters is already a challenge, and in many occasions the crew only has an estimation (in some cases a rough estimation) of the actual loading condition. This is a typical case for, e.g., container vessels, where the loading condition cannot be accurately determined using only the declared containers' weight (the situation will however improve by the introduction of the mandatory weighting of containers expected in 2016). In case of methodologies intended to determine the dynamic behaviour of the vessel at sea, in addition to the knowledge of KG/GM, it is necessary to know also the characteristic vessel periods (particularly roll period). An inaccurate evaluation of the roll period (or, equivalently, of the roll inertia) can lead to inaccuracies in the application of ship-specific operational guidance. It is therefore a challenge, from a regulatory perspective, to put in place uniform procedures which can guarantee that the guidance to the master is provided on the basis of accurate enough input data for the underlying computational tool.

A challenge which is also likely to be faced in the approval process, is associated with the uncertainty in the estimation of the parameters (e.g. roll damping, radii of inertia, wind coefficients, etc.) for carrying out the simulations aimed at providing ship-specific operational guidance. Indeed, many of the parameters used in the simulations will be affected by some level of uncertainty. Such uncertainty will then propagate to the final results, which, then, will also be uncertain. Therefore, the challenge for the approval process will be how to address this inherent level of uncertainty.

Another interesting aspect which is likely necessary to be properly taken into account in respect to the development and approval of ship-specific operational guidance is the use of active means for motion reduction (typically roll). When assessing present intact stability criteria, it is typical to neglect the effect of active anti-rolling means. However, neglecting active means when preparing ship-specific operational guidance can produce misleading guidance. A typical example is represented by active anti-rolling fins for certain vessels (e.g. cruise ships). Such anti-rolling devices tend to have a significant beneficial effect on roll motion at sufficiently high forward ship speed. Neglecting the additional damping effect of anti-rolling fins could lead to issuing operational recommendations to the master which are not properly exploiting the increase of forward speed (and thus damping) as a risk control option. Of course, taking into account active anti-rolling devices (e.g. stabilizing fins, anti-rolling tanks, etc.) introduces further complexity in the mathematical modelling which is to be used for developing operational guidance.

Another global challenge from a design and regulatory perspective is associated with the decision on when/how to accept a ship-specific operational guidance, instead of requiring a design modification or flagging the considered loading condition as "not seagoing". Indeed, there will be a region of high "safety level" where the vessel, in the considered loading condition, will comply without additional requirements. There will likely be a region of low "safety level" where the vessel, in the considered loading condition, will not comply at all. As a result, the loading condition will either be considered as "unacceptable" or design modifications will be required to increase the passive safety. However, there will be an intermediate region where it will be possible to ensure the required safety level by providing ship-specific operational guidance. How to measure the "safety level" and where to put the "boundaries" is a significant challenge from the technical and from the rule-development/approval perspectives.

Furthermore, in all these considerations, it was implicitly assumed that, given "ideally perfect operational guidance", the crew would respond appropriately by following them. The reality, however, is clearly fuzzier. Ship-specific operational guidance cannot be perfect for different reasons: approximation of the underlying mathematical modelling, inaccurate knowledge of environmental conditions, inaccurate knowledge of loading condition, etc. On top of this, the human factor becomes crucial, because, when dealing with operational guidance, the type of risk control option is active, and no longer passive, and typically, in intact condition, it could require human intervention (unless an automatic system is introduced). However, the human action is intrinsically uncertain, and the question arises of whether and how to take this uncertainty into account for the approval of procedures and tools for ship-specific operational guidance.

3. TOOLS AND METHODOLOGIES

To guarantee safety through operational measures, it is necessary to be able to predict large amplitude ship motions under the action of wind and waves. This requires using tools which are able to address nonlinear ship motions, and classical linear seakeeping tools are, in general, not appropriate for this purpose.

Simulation tools addressing nonlinear ship motions are, in the vast majority of cases, based on time-domain simulations. This makes the required computational time a challenging problem. In order for such tools to be viable in the framework of providing ship-specific operational guidance to the master it is therefore necessary to have at disposal tools which are fast enough, as well as application methodologies which reduces the required time for the computation of motions and subsequent provision/development of the operational guidance to an acceptable level. The acceptability level with respect to computational time depends on whether the tools and procedures are to be used in the design phase or in the operation phase.

As already said, in fact, three main categories of approaches can be envisioned for ship-specific operational guidance: pre-computation at the design stage, real-time computations on board during operation, and real-time computations onshore during operation. Different types of mathematical models can better suit different approaches. Indeed, tools and methods at various levels of detail can be utilised for nonlinear ship motions assessment.

Nowadays, the highest level of simulation complexity which is still compatible with the need for extensive series of simulations is represented by hybrid 6-DOF tools simulating the vessel freely manoeuvring in waves. The typically required computational time makes these tools more suitable for an application within a procedure targeting the design phase. However, under proper design of the methodology, they could also be implemented in a framework based on onshore real-time calculations using forecast weather data. In this moment, these tools are hardly applicable for real-time approaches using locally measured wind and sea conditions (e.g. through anemometers and wave radars, or using vessel motions to infer the sea spectrum). Nevertheless, such tools could ideally be implemented in frameworks intended for deterministic prediction of ship motions in a short time-horizon (of the order of minutes), provided the associated methodologies would prove to be robust enough and the prediction time-horizon would prove to be long enough to allow the actual implementation of some risk control option.

At reduced level of complexity there are several possible approaches, based on nonlinear models, typically with a reduced number of degrees of freedom. Such models are much faster, and therefore, in principle, more appealing, especially if the aim is the implementation of real-time, or near real-time approaches. However, the reduction in the model complexity is often achieved by targeting the model to certain specific failure modes (e.g. resonant roll, variations of stability in waves, manoeuvring-related problems such as surf-riding and broaching). As a result, such models should be used very carefully, with a clear understanding of the modelling limitations. Indeed, such specific dynamical models, targeted to specific failure modes, typically provide wrong operational indications if misused, i.e. if used outside their region of applicability.

Irrespective of the used dynamical model for the prediction of ship motions and/or for the identification of potentially dangerous conditions, there are a series of common challenges impacting tools and methodologies.

A challenge which was already anticipated in the previous section has to do with the description of the environment (wind and waves). Indeed, it is known that the actual environmental conditions can differ significantly from the idealised simplified and parameterised spectral models which are commonly used for simulation purposes. Sea and wind spectra encountered in operation shows larger shape variability than that which can be modelled by superimposing the classical two wave systems: wind waves (with spreading) and swell (with or without spreading). Also, more than two systems can coexist, with a significant potential variability in terms of relative direction. In this respect the question then arises of whether and, if so, to what extent, the differences between the actual environment and the parameterised simplified environmental conditions actually impact the capability of providing relevant operational guidance. In addition to this, questions are also open regarding the impact, on the relevance of the prediction, of introducing or neglecting nonlinear effects such as a nonlinear description of the wave field, breaking waves, rogue waves, etc.

With respect to environmental modelling, it is also necessary to bear in mind some other aspects. First of all, not all mathematical models are capable of taking into account multi-directional waves. This is the typical case for some 1-DOF models which were developed only for the long-crested sea case. As a result, environmental modelling limitations can be implicitly introduced by the used mathematical model, and the consequent impact on the prediction capabilities should be assessed. Furthermore, practical limitations exist regarding the modelling of the environment, depending on whether the operational guidance are developed through pre-computations at design stage, or whether the operational guidance are linked with real-time computations in operation. Indeed, taking into account the actual variability of the environmental conditions in a framework based on pre-computations at design stage is likely to be not viable due to the corresponding too large matrix of simulation scenarios. As a result, in such a framework, simplifications in terms of number of parameters for the modelling of the environment are necessary. Alternatively, calculations should be carried out on reduced sets of scenarios, assuming the other scenarios to be "safe" (e.g. avoiding unnecessary calculations in small significant wave heights). On the other hand, in a framework based on real-time computations, the actual environment could be exactly taken into account, at least in principle, provided that the information regarding wind and waves spectra are available (from measurement or forecast) and provided the tool and the procedure for issuing the guidance is able to appropriately use such information. There are also special situations where getting information regarding the environmental conditions can be difficult. It is the case, for instance, of inland navigation, where microclimate effects can be difficult to be captured in a real-time framework based on weather forecast.

An important point to be taken into account when considering tools and procedures to be used for operational guidance, is the fact that the framework, in general, has to be based on a probabilistic approach where the likelihood of an intact stability failure is typically required to be at acceptable probability levels, which can be very low. This means that failure events to be "discovered" (and for which guidance should be issued) can become rare events. This poses significant challenges in terms of procedure for assessing the risk level of a specific scenario. Indeed, direct Monte Carlo approaches require a large number of realizations to be able to quantify the likelihood of occurrence of rare events with sufficient accuracy. In some cases a direct Monte Carlo approach can become unfeasible, without introducing some more advanced calculation procedures. Procedures have been proposed making use of split-time approaches, wave-groups approaches, approaches based on first-order reliability methods, or approaches relying on extrapolation based on significant wave height. In most cases such approaches were proposed for the use in a design-level pre-computation framework, but potential could exist for their use also in a real-time calculation framework. In some cases such approaches have been designed for application in a route-optimization framework. In such case, translating them to an operational-guidance framework could be mostly a matter of computational speed.

Another important aspect to be taken into account when generating operational guidance relates to the manoeuvring behaviour of the vessel in wind and waves. In numerous mathematical models the (average) ship speed and the (average) heading angle are kept fixed. Although this is a useful assumption for assessing the behaviour of the vessel in the nominally defined conditions, such an approach misses a series of important characteristics. First of all this approach does not take into account the effect of active rudder control. There are phenomena, such as broaching, where the modelling of the rudder control has a significant effect on the outcomes of the assessment. Other phenomena which are not considered by constant (average) speed models are the involuntary speed reduction and the ship ability to keep the commanded course. These phenomena can make some combinations of speed and course not realistic because they would be practically not achievable by the vessel. Furthermore, neglecting speed variations can miss the speed reduction in high groups in head sea, as well as the typical prolonged staying of the vessel on the wave crest in following waves due to asymmetric surging, and this can influence certain phenomena (e.g. parametric roll, pure loss of stability, surf-riding and broaching). Whether taking into account all these aspects is something to be done directly by the ship motions simulation model, or whether this can be done by intermediate approaches mixing different mathematical models, is, presently, a matter of investigation. A matter of investigation is also the understanding of the extent to which the mentioned modelling aspects are affecting the issuing of operational guidance.

A further matter connected with tools and methodologies for operational guidance is the definition of "stability failure", because such definition cannot be considered to be totally independent of the tool used for the computations. The definition of "stability failure" needs to be consistent with, and needs to properly account for, the capabilities and limitations of the tool which will eventually be used for the evaluation of the ship behaviour. For instance, while a 6-DOF tool is able to provide the full kinematics of the vessel, the same cannot be said, in general, for models with reduced number of degrees of freedom (e.g. 1-DOF models). In this latter case additional assumptions and approximations need to be introduced to try taking into account the missing degrees of freedom, when this is needed. This eventually reflects in the overall capability and accuracy of different tools to take into account stability failures associated with, e.g., accelerations. Such situation needs therefore to be properly accounted for when defining the "failure conditions" to be used.

Other types of less conventional approaches have been proposed, or can be envisaged, for issuing operational guidance in a real-time framework, where use is made of specifically designed and trained Artificial Neural

Networks (ANN). Although such approach is appealing, thanks to the associated computational speed and adaptability, some challenges for its use are evident. The model needs to be properly and extensively trained at the design stage (with possible update during the operation), through appropriate simulations. In addition, and connected with the training phase, attention must be paid to the use of ANN outside the training range, since such approaches typically lack extrapolation capabilities.

When considering approaches for a real-time calculation framework, two options have been mentioned: onboard computations and onshore computations (through an onshore support team). These two approaches significantly differ in terms of availability of computational resources and expertise of users, and this, in turn, reflects on the fact that significantly different models and/or procedures are expected to be used in the two cases. In case computations are carried out onboard, fast and simple models are expected to be employed, whereas more complex and computationally intensive models can be used for calculations carried out onshore. The same is valid for the calculation procedures to be used. Indeed, even fast simulation models can result in slow computations if the application procedure requires too many calculations for the available resources. In case calculations are carried out onboard, such procedures shall therefore be fast and simple (possibly based on simplified nonlinear frequency domain approaches). On the other hand calculation procedures based onshore can benefit, and therefore be allowed to require, significantly larger computational resources.

Formulating ship specific operational guidance is hence a trade-off between accuracy and simulation time, and also between accuracy in the ship dynamics modelling and the accuracy in the sea state representation. In his context, on one extreme there are 6-DOF simulation tools having the potential for providing a higher level of accuracy, which is however paid at the cost of the increased simulation time. On the other extreme, simplified frequency domain methods exist, for example, for the determination of stability limits for parametric rolling and pure loss of stability from estimated spectra of GM variation, which are determined from GM variation transfer functions and wave spectra according to linear response theory. Such methods require very small computational effort, making them applicable for real-time computations. However the reduced computation time is paid by the likely reduction in the prediction accuracy. Where the optimum trade-off is positioned is a matter, on the one hand, of goals and, on the other hand, of technological and theoretical evolutions. This means that the optimum trade-off is something moving with time, experience and research & development.

4. IMPLEMENTATION IN OPERATION

The onboard implementation of means for providing operational guidance to the master is, evidently, the final goal. It is also evident, from the discussion so far, that a series of technological challenges are associated with the actual implementation of such a system. While some of such challenges are of general nature, some others, again, depend on how operational guidance is assumed to be provided: on the basis of pre-calculations at design stage, on the basis of real-time onboard calculations, on the basis of real-time onshore calculations, or a mixture of the three. Challenges associated with theoretical and technological aspects, however, are only one part of the picture. Aspects associated with ergonomics (human factors) are also important for a successful implementation of an onboard operational guidance system, which, in essence, is (part of) a decision support system. Indeed, in a system development phase, the attention is typically focussed on calculation methods. However, moving from such phase to the later phase of the implementation, clearly requires taking the matter of interaction with crew in due account.

Two fundamental aspects are directly linked with onboard implementation: loading condition on one side, and prevailing weather conditions on the other side. Indeed, irrespective of how the operational guidance is actually determined (pre-calculations or real-time calculations), for an onboard implementation, it is clearly necessary for the system to know the present (or future, in case of forecasts) loading condition and the present (or future, in case of forecasts) weather conditions. It is therefore necessary that an actual onboard implementation will be able to get information regarding the loading condition and weather conditions.

Regarding the loading condition, the starting point is evidently the loading condition as known (estimated) at the departure, combined with the sounding of the tanks during the voyage (or an estimation of consumptions), and/or combined with the information on loaded/unloaded cargo weights in case this is relevant to the vessel operation. However, such an approach is limited with respect to two aspects. First, it gives an estimation of the actual loading condition which can be affected by uncertainty. Second, typically, it does not give information regarding the inertia, which needs therefore to be estimated, introducing, again, uncertainty. In order to provide accurate operational guidance, it is therefore necessary to try implementing approaches which can increase the accuracy in the knowledge of the relevant mechanical characteristics of the vessel. For instance, to increase the accuracy in the knowledge of GM, it could be envisioned to systematically perform some kind of simplified inclining test at the departure, something which some vessels/operators are already doing. Alternatively, methods could be devised for carrying out an approximate GM determination while at sea. Clearly, appropriate approaches should also be implemented in order to have also a sufficiently accurate knowledge of the trim and displacement. To this end, the common procedure of direct reading of draught marks in port can be supplemented by, e.g., approaches making use of data from automatic draught measuring systems which, following proper processing, could be used to provide a real-time estimation of trim and displacement during navigation (at least in time windows of sufficiently mild weather conditions). However, the knowledge of GM, for a given trim and displacement, is not sufficient for predictions addressing ship dynamics for safety purposes. In such case the rolling period (or rolling inertia) is one of the parameters which need to be properly known. To this end it could be envisaged to implement procedures for systematically carrying out small roll decays, at least at the departure, for estimating the roll period. Alternatively, real-time monitoring systems could be used to estimate the natural roll period of the vessel during operation. Other parameters could also be necessary such as, e.g., the pitch inertia. For the determination of the pitch inertia, real-time monitoring of the pitch motion, possibly linked with knowledge of local weather conditions, could be of help. Of course, none of these approaches can be considered more than an estimation of the actual quantity of interest. However, trying to increase the accuracy of the estimation represents a means for increasing the accuracy of the overall decision support system.

Once the actual loading condition is assumed to be known with a sufficient accuracy, the other big challenge is the knowledge of the weather conditions, i.e. wind and waves (and possibly current). Two main approaches can be implemented onboard in this respect: use of forecast data, or use of data from real-time measurements. A combination of the two can also be envisaged, where, for instance, forecast data could be corrected by an analysis of systematic comparison of forecast and actual measurements. In general, however, the type of measuring system could be tied to the type of procedure which is used for issuing the operational guidance. Indeed, guidance based on pre-computations could in principle make use of real-time estimation/measurements of weather conditions. However, a challenge in this case is faced: how to use pre-computed data in nominal weather conditions for issuing guidance associated with the presently measured ones? Such challenge actually occurs also with forecast data, whenever the forecasted weather condition does not (sufficiently) match any one in the set of those originally used in pre-calculations. Real-time measurement, as well as forecasted data, can be used, instead, at least in principle, without difficulties, whenever sufficiently fast algorithms are used for the issuing of operational guidance. However, this requires algorithms able to account for the complexity of the environment (directional sea spectra, wind spectrum, etc.). On the other hand, real-time monitoring is typically of no use if operational guidance approaches are based on relatively slow computations (onboard, but more likely onshore). In such case the only viable option for issuing operational guidance based on motions statistics is the use of forecast data. Alternatively, deterministic short-time horizon (of the order of minutes) guidance could be potentially based on real-time measurements. In this case, however, wave radars should be used.

Also connected with the monitoring of weather conditions, it is worth mentioning a relevant fact, providing some associated brief considerations. Presently, the IMO MSC.1/Circ.1228, which basically represents the prototype of ship-independent (i.e. generic) operational guidance, assumes that a monitoring of the weather conditions based on observations by the crew is sufficient. The question, then, is weather this assumption can be considered valid for a modern ship-specific operational guidance system. It is indeed known that the level of accuracy of visual observations is limited, and the example case of (basically impossible) estimation of weather conditions by visual observations at night should serve as a sufficient example to show the limitation of the approach. Therefore, considering that the accuracy of the predictions of ship motions is typically limited by the element of the prediction chain with the higher combination of inaccuracy and sensitivity coefficient, it is very likely that environmental conditions estimated on the basis of visual observations cannot be considered compatible with a robust ship-specific operational guidance system.

The other mentioned challenge for a practical successful onboard implementation is associated with human factors and, in details, with the relation between the system and the crew. One important aspect to be taken into account is the usability and understanding by the crew of the information given by the support system. In this respect it is important that the post-processing of the data is made with the aim of providing immediately and clearly understandable information regarding the potential danger level of the conditions. Polar diagrams (speed and course for the present weather scenario) are a typical way of presenting results based on the analysis of, for instance, some statistical quantity relevant to the ship safety (e.g. expected mean roll amplitude, or maximum roll amplitude for a given nominal exposure time, or similar data regarding the acceleration, or quantities associated with cargo failure). Guidance information, based on the processing of such data, should be provided using appropriate colour coding for immediate understanding, and the parsimonious use of audio alarms could also be considered. Similar polar representations can also be used to report regions of speed and course leading to specific problems (e.g. parametric roll, pure loss of stability, manoeuvring and course keeping problems, etc.).

With reference to the interaction of the system with the crew, it is also important to be sure that the system is accurate enough (and not, for instance, too conservative) for the crew to rely on it when taking decisions. Experience has shown that the trust of the crew in operational guidance and decision support information is very much dependent on how well the information corresponds to their own experience of the operational situation.

Another important aspect for a successful holistic approach to safety through operational measures is associated with the training/education of the crew. The crew is indeed likely to take in low consideration guidance information received from a system that is not sufficiently well understood in terms of underlying theoretical and/or technical background. Also, not all crews are fully aware of the more complex stability failure modes. Enhancing the crew education and awareness is hence of utmost importance. Such education should consider general stability aspects as well as certain aspects regarding the specific vulnerabilities of their ships. As an example, just informing crews about the outcomes of SGISC Level 2 assessment for their particular ship, would already imply a significant safety improvement compared to the current situation, since it would give a better awareness of the susceptibility of the vessel to different phenomena in a transparent way. Part of the process of education could also be based on follow up from accidents, or near-accidents. In this case, the recording, and following analysis together with the crew, of the actual weather conditions and ship motions at the moment of the (near-)accident, could prove being of great help and impact.

Furthermore, education and training of crew could also be enhanced by increasing the use of virtual reality simulators embedding also operational guidance systems. This would have two main benefits. On the one side it could help the crew in familiarising with the operational guidance system. On the other side, it could help in improving and updating the operational guidance system on the basis of the experience made during the virtual simulations and on the basis of the feedback gathered from the users.

5. FINAL REMARKS

Although the overall ship safety in intact condition is the result of a combination of design and operational measures, operational safety measures are presently neither facilitated nor sufficiently normed by the regulators. This situation does not promote the implementation of approaches aimed at increasing safety through proper and cost-effective operational measures. At the same time, however, clear and large potentialities exist for increasing the fleet safety level by properly combining passive design measures with active operational risk control options. It seems, therefore, that time could be coming for systematically considering operational measures as a recognised and normed integral part of a holistic approach to ship safety from the point of view of stability. However, several challenges are to be faced, requiring efforts from the point of view of research & development and from the point of view of the rule-making process. In this context, the scope of this paper has been to identify such open challenges and to provide, in general, food for thoughts for stimulating a discussion on this topic, with specific attention to the intact condition. The aim of the discussion should be to provide ground for further proceeding towards the goal of implementing a virtuous integrated approach to ship stability safety which gives due credit to effective and robust operational risk control options.

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7. REFERENCES

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